Recent Developments in High Energy-Density Plasma Physics

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High energy-density physics (HEDP) is one of the five technical pillars of the Stockpile Stewardship Program, and it is now recognized as an important, multidisciplinary area of research to be emphasized at the national level [1]. Conventionally, HEDP is defined as the study of matter under extreme pressures, in excess of one megabar. As Fig. 1 notes, HEDP science also is relevant to astrophysics and fusion energy research.

A plasma's ionic charge states, and the many-body correlations among its particles, influence its equation of state, its transport coefficients, and its radiation spectrum, so it is useful to illustrate HEDP effects on these basic quantities. Figure 2 reveals that even a "simple" issue like ionization balance can be difficult to treat accurately in dense plasmas: the Saha equation (appropriate at low densities) predicts mean charge states <Z> that differ substantially from the values of <Z> predicted by the Thomas-Fermi equation (appropriate at high densities). Moreover, both of these prescriptions incorporate simplifying assumptions that, at best, are questionable under HEDP conditions, and neither is valid for nonequilibrium plasmas. Further, the Saha equation yields charge state fractions—essential for spectroscopy—but the Thomas-Fermi equation yields just <Z>.

A second example of HEDP effects is shown in Fig. 3, which plots radial distribution functions $g(r) = n_i(r)/n_i$ in a one component plasma of ions (charge Ze) embedded in a uniform density background of electrons ($n_e = Zn_i$), for different values of the Coulomb coupling parameter $\Gamma = (Ze)^2/a\,\Theta$, where Θ is the temperature in energy units and $a = (3/4\pi\, n_i)^{1/3}$ is the mean inter-ion spacing. Radial distribution functions for the larger Γ-values exhibit peaks that indicate substantial short-range order in the plasma.

Within the past year, we reviewed many of the concepts and methodologies (from hydrodynamics, condensed matter, statistical, plasma, and atomic physics) that underlie the field of HEDP [2, 3]. Novel ideas and experiments are needed to better understand and model matter that may be far from equilibrium, strongly coupled by Coulomb interactions, and/or involve degenerate electrons, so one goal of our work was to

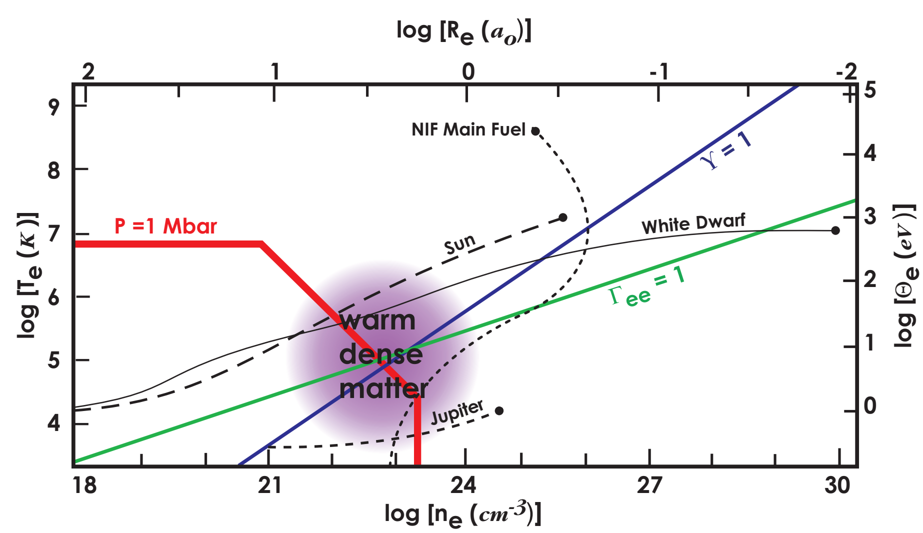

***Figure 1—** The HEDP regime in the temperature-density plane. Above and to the right of the dark red line, the pressure of matter plus radiation exceeds 1 Mbar. Plasmas below the line $\Gamma_{ee} = 1$ are strongly coupled, and those below the line $Y_e = 1$ are degenerate. The tracks shown mark conditions within the Sun, Jupiter, a white dwarf star, and an imploding ICF capsule.*

identify challenging problems in this subject that are important generally to the Nuclear Weapons Program and that could be tackled effectively with present Los Alamos National Laboratory capabilities.

Due to particular Theoretical (T) Division strengths and interests in theory and simulation, three important HEDP subjects have now been identified for emphasis:

Quantum simulation methods (our essential enabling "technologies"—quantum Monte Carlo, quantum molecular dynamics, and wavepacket molecular dynamics); *Radiation Hydrodynamics* (equation of state for mixtures, opacities of inhomogeneous media, turbulence effects, astrophysical and fusion applications); and *Nonequilibrium Phenomena* (relaxation, particle transport, nuclear reactions, laser-plasma interactions, intense magnetic fields).

At last count, more than a dozen specific projects within these areas are already underway or are being organized. These T-Division efforts involve partnerships with both theoretical (e.g., Applied Physics and Computer and Computational Sciences) and experimental (e.g., Physics, Materials Science and Technology, and the Los Alamos Neutron Science Center) divisions at LANL, as well as external laboratories and universities.

[1] "Frontiers in High Energy Density Physics," National Research Council, 2003.
[2] M.S. Murillo, "Strongly Coupled Plasma Physics and High Energy-Density Matter," *Phys. Plasmas* **11**, 2964 (2004).
[3] J. Weisheit and M.S. Murillo, "Atoms in Dense Plasmas," in *AIP Handbook of Atomic Molecular and Optical Physics,* 2nd ed. (Springer, New York, in press).

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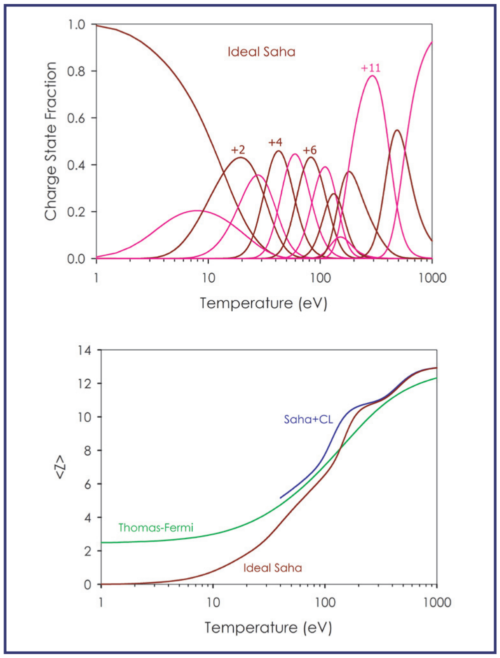

Figure 2— ***The variation of mean charge state <Z> with temperature in an aluminum plasma at solid density (2.70 g/cm^3), as predicted by the Saha and Thomas-Fermi equations (lower panel. Corresponding Saha charge state fractions (upper panel).***

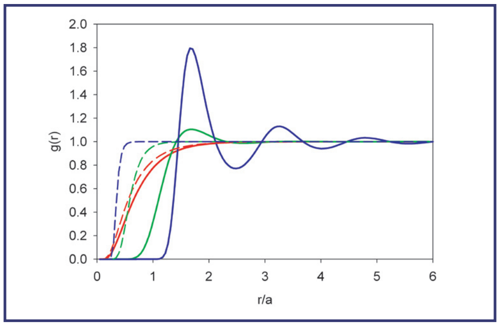

Figure 3— ***Radial distribution functions g(r), which measure the expected density of ions neighboring one at the origin, are plotted versus scaled distance r/a, for Γ = 1 (red), Γ = 10 (green), and Γ = 100 (blue). Solid lines: hypernetted-chain theory. Dashed lines: analytic model using Debye potential of mean force.***

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